A Two Phase Interleaved Boost Single Stage PFC Converter using Flying Capacitor

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Abstract---**The equipment connected to an electricity distribution network customarily needs rectification. In order to decrease DC voltage ripple, a Single phase diode rectifier utilizes a large electrolytic capacitor which yields a non-sinusoidal line current. So power factor correction (PFC) techniques are required. The boost topology is utmostwidespread than others in PFC applications. Thus a two phase interleaved boost single-stage PFC converter using flying capacitor is proposed in this paper. Due to its interleaved structure, the proposed converter can operate with reduced input current ripple and peak switch currents.The proposed system is simulated in MATLAB/SIMULINK and the performance parameters such as power factor (PF) and total harmonic distortion (THD) are computed.**

Key terms-- **power factor, power factor correction, total harmonic distortion, interleaved boost converter, single stage converter, pulse width modulation.**

I. INTRODUCTION

Most of the electronic equipment is supplied by 50 Hz utility power. More than 50% of this power is handled through some kind of power converter. In order to convert AC voltage to DC voltage, certain power converters utilizes a diode rectifier monitored by a bulk capacitor. When the line voltage is higher than the DC bus voltage, then the input line current contains rich harmonics. Due to the presence of harmonics the power factor can be lowered. By adding a passive filter the power factor can be improved [1]. One major disadvantage by adding this passive filter is that itis bulky and inefficient. So to achieve a good power factor a power factor correction (PFC) stage has to be introduced to the existing equipment. The advantage of using this PFC technique is that it reduces current harmonics in an utility systemwhich was produced by nonlinear loads [2].

The operation of Single phase diode rectifiers is to rectify the input ac line voltage and filter it with large capacitor. By utilizing the filter capacitor, the ripple present in the output voltage was reduced but it introduces distortion in the input current then the power factor gets reduced. So PFC techniques are used. Generally there are two types of PFC techniques. One is passive PFC technique and another one is active PFC technique. By utilizingpassive PFC techniquethe improvements are limited. In order to get a good result active PFC technique [3] can be used. Boost converter is considered as the utmost widespread topology for active PFC as it draws continuous input current. But due to rise and fall of the inductor current in the boost converter there will be an presence of ripple in the input current. This problem can be overcome by using two phase interleaved boost converter [4],[5],[6]. The operation of interleaved boost converter is that the two boost converters are in 180^0 out of phase. As the input current is the summation of two inductor currents then the inductor's ripple currents cancel out each other as it operates in 180^0out of phase and also the reduction in the input ripple current is obtained.While considering active PFC the switching converters are used to shape the input current in phase with the input voltage waveform then the power factor becomes nearer to unity and it behaves like a pure resistive load. When comparing with the passive PFC, the active PFC has more advantages such as high power factor, reduction in total harmonic distortion. The active PFC can be classified into two-stage and single-stage power factor corrected converters. This paper introduces a two phase interleaved boost single stage PFC ac-dc converter using flying capacitor with standard pulse width modulation (PWM) which provides higher power factor, reduction of total harmonic distortion and also provides better control. The proposed converter operation is explained. However, the single-stage PFC converter can achieve high PF and voltage regulation at the same time [7],[8]. The proposed single stage PFC converter is shown in fig. 6. The typical waveform for the proposed converter is shown in fig. 7.

II. SINGLE PHASE DIODE RECTIFIER

To convert ac-dc single phase diode rectifiers are commonly used. But a fair amount of ripple will be present in the rectified dc voltage. An easy way to reduce this ripple is to use a filter capacitor. A single phase diode rectifier with a filter capacitor is shown in fig.1.

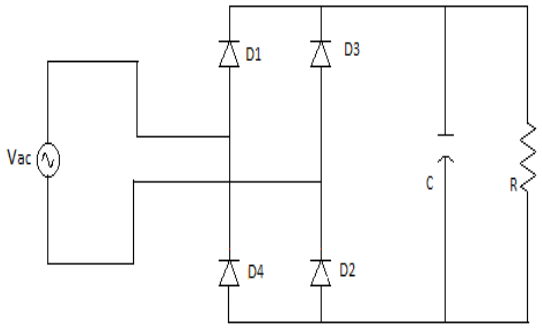


Fig.1.Single phase diode rectifier with filter capacitor

By utilizing this filter capacitor it reduces the ripple from the output voltage, but it introduces distortion in the input current and also draws discontinuous current from the supply, in short pulses. When the input ac voltage is greater than the capacitor voltage then only the capacitor draws pulsating current which occurs at the line voltage peaks. So due to the utilization of this filter capacitor the power factor becomes poor.

III. BOOST CONVERTER

In order to overcome the above problem of pulsating input current PFC techniques are used. Best result can be gained by using active PFC techniques based on switch mode power converters. Boost converter is considered as the utmost widespread topology for active PFC as it draws continuous input current.The circuit diagram of boost converter is shown in fig.2.

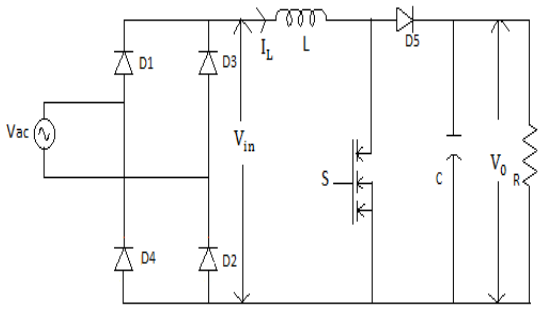


Fig.2. Boost Converter

The current $I_L$raises when the switch S is ON and this current flow through inductor L. The current

I_L decreaseswhen switch S is OFF andthis current flow through L, diode D5, C, and R. The current I_L falls until switch S is turned ON again.

So when switch S is ON:

$$\frac{dI_L}{dt} = \frac{V_{in}}{L} \quad (1)$$

Again when switch is OFF:

$$\frac{dI_L}{dt} = \frac{V_o - V_{in}}{L} \quad (2)$$

Here V_{in} is the rectified input voltage and V_o is the output voltage.

IV. INTERLEAVED BOOST CONVERTER

Due to the rise and fall of the inductor current in the boost converter a ripple will be present in the input current. This problem can be eliminated by using interleaved boost converter. The interleaved boost converter is shown in fig.3.

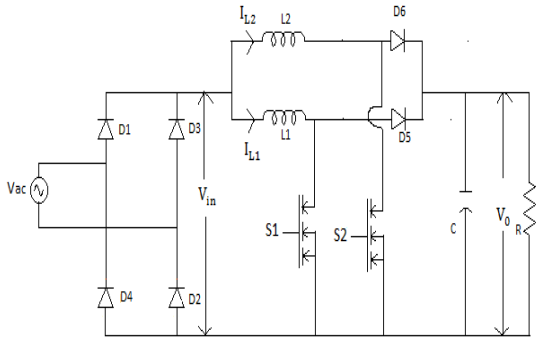


Fig.3.

Interleaved Boost Converter

The two boost converters operate in 180^0 out of phase in interleaved boost converter. The input current is the summation of two inductor currents I_{L1} and I_{L2} then the inductor's ripple currents cancel out each other as it operates in 180^0 out of phase.

When switch S1 is ON and switch S2 is OFF

$$\frac{dI_{L1}}{dt} = \frac{V_{in}}{L1} \quad (3)$$

$$\frac{dI_{L2}}{dt} = \frac{V_o - V_{in}}{L2} \quad (4)$$

When switch S1 is OFF and switch S2 is ON:

$$\frac{dI_{L1}}{dt} = \frac{V_o - V_{in}}{L1} \quad (5)$$

$$\frac{dI_{L2}}{dt} = \frac{V_{in}}{L2} \quad (6)$$

The two inductor currents will be out of phase and cancel out the ripple of each other if:

$$\frac{V_{in}}{L1} = \frac{V_o - V_{in}}{L2} \quad (7)$$

$$\frac{V_o - V_{in}}{L1} = \frac{V_{in}}{L2} \quad (8)$$

The above two equations i.e. equation (7) and equation (8) will be satisfied if and only if L1=L2 and $V_0 = 2V_{in}$.

V. DESIGN CONSIDERATION OF INTERLEAVED BOOST CONVERTER

While designing an interleaved boost converter the following steps are to be included:

1. Choice of Duty Ratio:

As the number of phases considered in this paper is two, 50% of the duty cycle will be the best choice. When D=0.5 it result in less ripple when compared to other duty ratios. Thus the duty ratio is calculated as,

$$D = \frac{V_o - V_{in}}{V_0} \quad (9)$$

Where, V_0 indicates the output voltage in volts,
V_{in} indicates the input voltage in volts and
D indicates the duty ratio.

2. Optimal Number of Phases:

As the number of phases is increased the ripples will be minimum. But increasing the number of phases will definitely result in the increase in cost and it becomes difficult to the entire circuit. So the number of phases is considered as two in this paper.

3. Design of Inductance and Capacitance:

The inductor and capacitor values can be established using the formula given below [10]-[12].

$$C = \frac{V_o DT}{R \Delta V_0} \quad (10)$$

Where, V_0 indicates the output voltage in volts,
D indicates the duty ratio,
R indicates resistance in Ω.
T indicates the switching period in seconds and
ΔV_0 indicates the change in the output voltage.

$$L = \frac{V_S D}{\Delta iLF} \quad (11)$$

Where V_S indicates the source voltage in volts,
D indicates the duty ratio,
F indicates the frequency in hertz and
ΔiLindicates the inductor ripple in ampere.

4. Choice of Coupled Inductor:

Selection of coupled inductors for the IBC is found by using the following equation [13].

$$L_{eq} = \frac{V_{in} DT}{\Delta I_{phase}} \quad (12)$$

Where, V_{in} indicates the input voltage in volts,
D indicates the duty ratio,
Tindicates the switching period,
ΔI_{phase} indicates the phase ripple current in ampere.

The phase current ripple is decided by L_{eq} and it is given by,

$$\Delta I_{phase} = \frac{V_{in} DT}{L} \cdot \frac{1+\alpha+2\alpha\frac{D}{1-D}}{1+\alpha-2\alpha^2} \quad (13)$$

Where, V_{in} indicates the input voltage in volts,
D indicates the duty ratio,
T indicates the switching period,
L indicates the self-inductance in mH and
α indicates the coupling coefficient.

Self-inductance of the coupled inductor is given by,

$$L = \frac{1+\alpha\frac{D}{1-D}}{1+\alpha-2\alpha^2} L_{eq} \quad (14)$$

To find the values of L_m and L_k, the input current is calculated as the ratio of power to that of voltage.

The mutual inductance L_m can be found by the following equation.

$$L_m = \alpha . L \quad (15)$$

The leakage inductance L_k can be calculated as

$$L_k = (1-\alpha) . L \quad (16)$$

VI. ACTIVE PFC

For high quality rectifiers active power factor correction techniques are used. Active PFC circuits form the input current waveform into a sinusoidal form in phase with the supply voltage wave form. On the other side it offers a regulated dc output voltage. Active PFC circuits behave like a resistor at the side of the converter. Generally power factor of active PFC circuits is nearer to unity with lower THD less than 5%. Active PFC techniques can be divided into two approaches:

1. Two stage approach
2. Single stage approach

Active Two-stage approach:

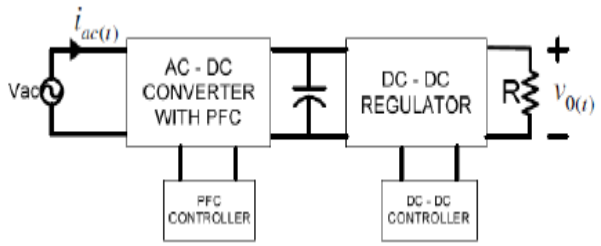


Fig.4. Two-stage Converter

A two-stage front end converter comprises of a PFC pre-regulator circuit and then followed by a DC/DC converter which was utilized to regulate the DC output voltage. In this approach, the bus capacitor is employed between the two front-end converters. The advantage of using this active two-stage PFC converter is that it has good input power factor and can be used in wide ranges of input voltage and output power but it needs two separate switches, converters and controllers so that the cost, size and complexity has been increased which becomes an disadvantage of this approach.

Active Single-stage approach:

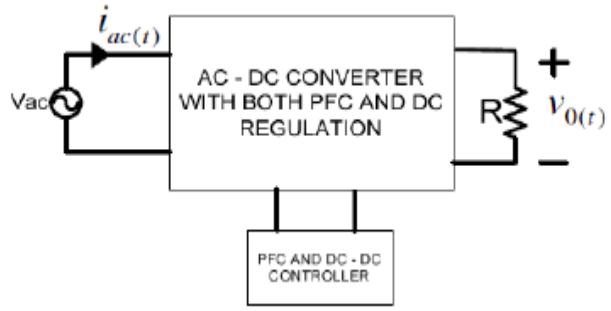


Fig.5. Single-stage Converter

Single-stage PFC converters connects both PFC front-end converters and DC/DC converters into a single converter stage. The advantage of using this approach is that the cost, size and complexity can be reduced because of the reduced number of switches and controllers needed to shape the input current and to regulate the DC output voltage.

VII. OPERATION OF PROPOSED CONVERTER:

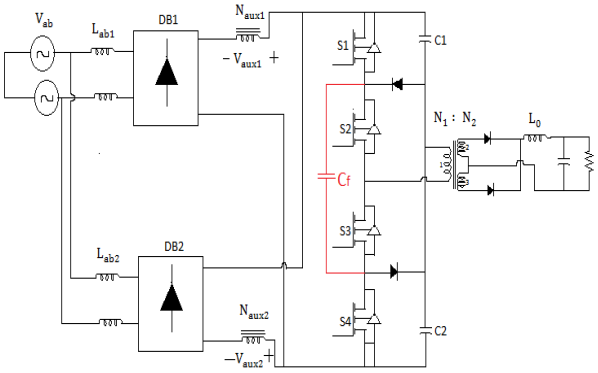


Fig.6. Proposed Single Stage ac to dc converter

The proposed single stage ac to dc converter is shown in fig.6 and its typical waveform is shown in fig.7.

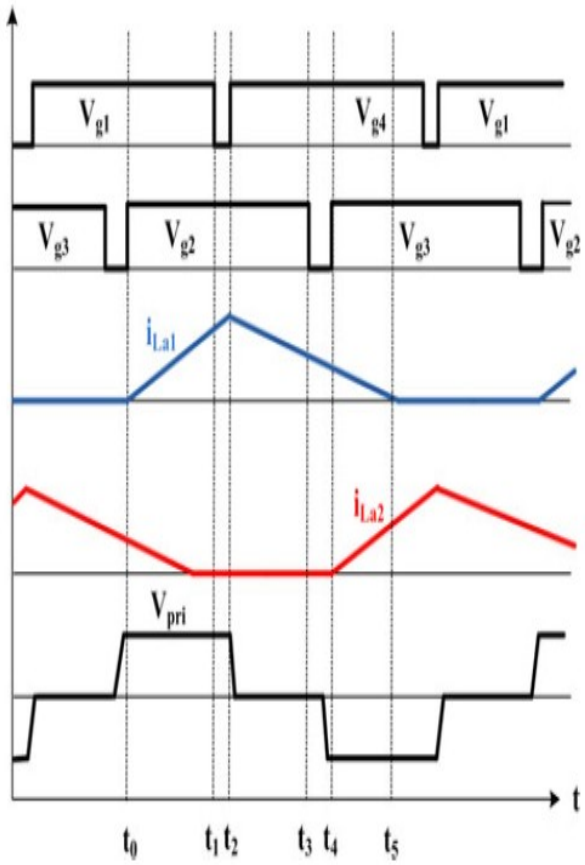
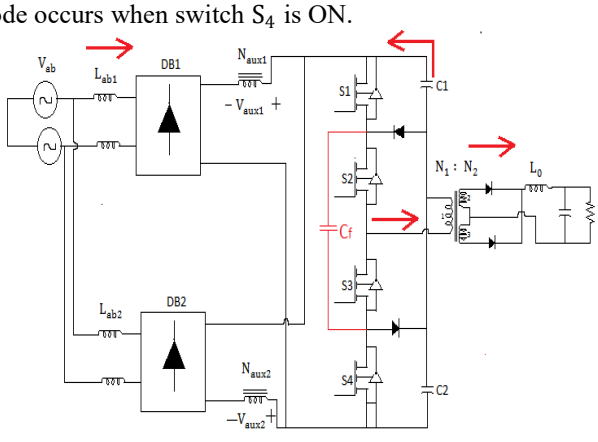


Fig.7. Typical waveforms for the proposed converter

The converter has the different modes of operation during a half switching cycle.

Mode 1 ($t_0 \leq t \leq t_1$):During this mode of interval, the ON switches are $S_1$and S_2. It should be well-known that both the dc bus capacitors and the flying capacitor are going to be charged to half of the dc bus voltage. In this mode, energy flows from dc bus capacitor $C_1$to the output load. As a result of magnetic coupling, a voltage being appeared across Auxiliary Winding 1 that can beequivalent to the dc bus voltage, but having with opposite polarity. Finally this voltage cancels out the total dc bus capacitor voltage then the voltage at the diode bridge output becomes zero, and there is a rise in input currents in bothL_{a1} and L_{b1}.

Mode 2 $t_1 \leq t \leq t_2$): During this mode of interval, $S_1$is OFF, and S_2still remains ON. The energy which has been stored in the input inductor during the previous mode starts is going tobe transferred into the dc bus capacitors. The end of this mode occurs when switch S_4 is ON.



(a)

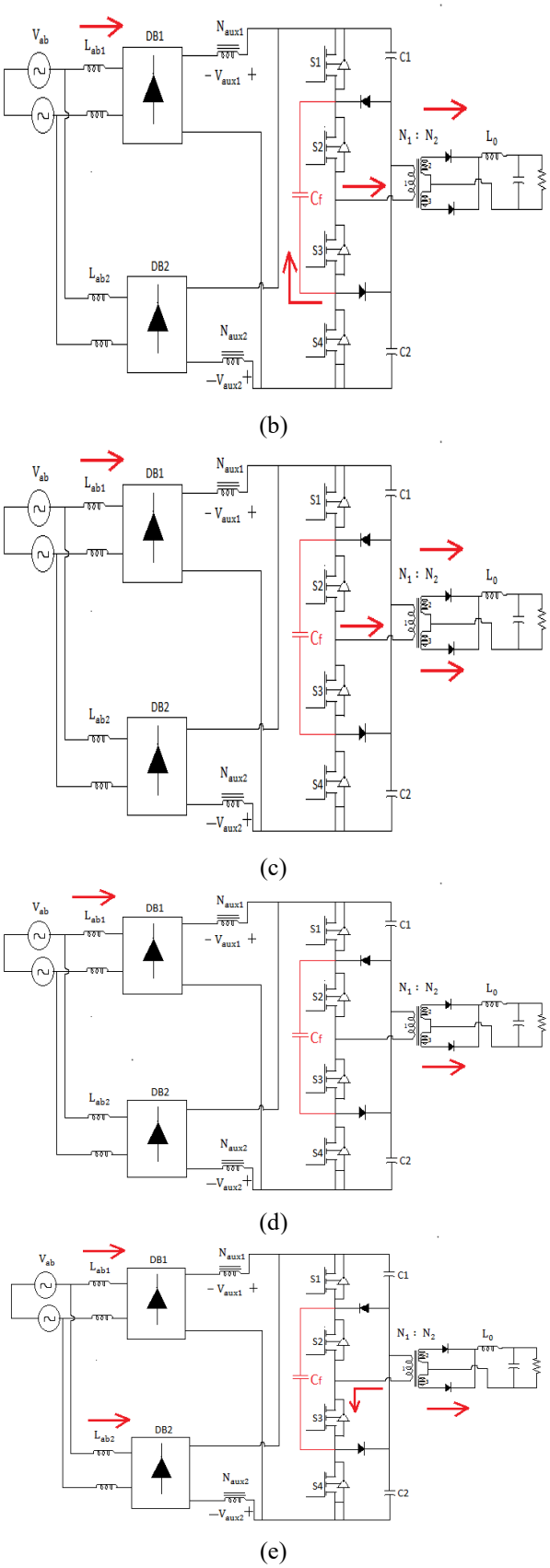


Fig.8. Modes of operation(a) Mode 1($t_0 \le t \le t_1$). (b) Mode 2 $t_1 \le t \le t_2$). (c) Mode 3 ($t_2 \le t \le t_3$). (d) Mode 4 ($t_3 \le t \le t_4$). (e) Mode 5 ($t_4 \le t \le t_5$)

Mode3 ($t_2 \le t \le t_3$) :During this mode of interval,switch$S_1$is OFF and switch S_2still remains ON. The energy which has been stored in the input inductor during the previous mode starts is also been transferred into the dc bus capacitors then the voltage appearing across Auxiliary Winding 1 is zero. The primary current of the main transformer flows through diode$D_1$and switchS_2. In regard to converter's output section, the load inductor current freewheels in the secondary of the transformer, which describes a voltage across the load filter inductor that is equivalent to $-V_L$.

Mode 4 ($t_3 \le t \le t_4$):During this mode of interval, both the switches $S_1$and $S_2$are OFF. The energy that has stored in L_1 continues to be transferred into the dc bus capacitor. If the energy in the leakage inductance is enough then the current will flow through the body diode of switchS_3. Finally this current also charges C_2 through the body diodes of S_3 and S_4.The end of this mode occurs when switch S_3 is ON.

Mode 5 ($t_4 \le t \le t_5$):During this mode of interval, both the switches S_3 and S_4 are ON and thus the energy flows from capacitor C_2 to the load then the voltage appears across Auxiliary Winding 2 equivalent to the dc bus voltage, but having with opposite polarity to cancel out the dc bus voltage. Finally the voltage across the boost inductor L_2 is only the rectified supply voltage of each phase, and there is an increase in the current flowing through each inductor. The end of this mode occurs when the energy stored in L_1 is entirely transferred into the dc bus capacitor. For the remaining of the switching cycle, the converter drives through Modes 6-10, which is similar to Modes 1-5 except that the switchesS_3 and S_4 are ON instead of S_1 and S_2 and the bridge diode DB_2 conducts current instead of DB_1.

Finally the input current is the summation of both the currents of I_{L1} and $I_{L2}$with each inductor having a discontinuous current. On the selection of proper values for $L_{a1} = L_{b1}$ and $L_{a2} = L_{b2}$ the two inductor currents can be made to overlap each other to make the input current continuous. As the operation of interleaved boost converter is that it is 180^0 out of phase then the two inductor ripple currents cancel out each other and lastly getting the reduction in input ripple current.

It should be noticed that a standard phase-shift PWM can be employed in the converter. The usage of a standard phase-shift PWM IC is to produce the gating signal. The switches S_2 and S_3 are not permitted to be ON at the same time, and also the switches S_1 and S_4 are not permitted to be ON instantaneously as well. Whenever the switches S_1 and S_2 are ON or S_3 and S_4 are ON then the converter is said to be an energy-transfer mode. In the same way whenever the switches S_1 and S_3 or S_2 and S_4 are ON then the converter is said to be in a freewheeling mode of operation. The occurrence of alternating energy transfer and freewheeling modes during a switching cycle resembles to the same arrangement of modes that happens in a standard two-level phase-shift PWM full-bridge converter.

VIII. FLYING CAPACITOR VERSUS DIODE-CLAMPED MULTILEVEL THREE-PHASE SINGLE-STAGE CONVERTER

The proposed interleaved boost converter topology using flying capacitor can guarantee a ZVS turn-on for its very top and the bottom switches in such a way that the converter presented in [14] cannot. For understanding an easy purpose, first consideration standard two-level ZVS_PWM dc-dc full-bridge converter which operates with a phase-shift PWM. For this type of converter, the leading leg switches (the switches that are turned ON when the converter enters a freewheeling mode of operation) of the converter can be switched ON with ZVS. This is because the transformer primary current is lead by reflected output inductor current during this shift then

there is adequate energy available to switch ON the leading leg switches with ZVS. In the lagging leg switches (the switches that are turned ON when the converter is leaving a freewheeling mode) that may lose their capability to switch ON with ZVS under light-load conditions as the leakage inductance energyis only at the transformer primary that is presented for the purpose of discharging and charging the proper switch output capacitances.

At this instant when switch S_1 is turned OFF then the converter is said to be entering into the freewheeling mode of operation. The leaving of this freewheeling mode of operation is by turning OFF of switch S_1 and the immediate turning ON of $S_3$and S_4. The only leakage inductance energy that is available during this shift is used to turn S_3 and S_4 ON with ZVS. In the similar fashion the switchesS_1 and S_2 are turned ON when the converter is leaving the other freewheeling mode of the switching cycle, again, with the leakage inductance energy that available only to discharge the output capacitances.

In regard to the proposed converter, it can be noticed that when the switchesS_1 (or S_4) are going to be turned OFF and also when the converter is entering into a freewheeling mode of operation, the energy that is available to charge and discharge the output capacitances of $S_1$and $S_4$is the energy stored in leakage inductance and the energy in output filter inductor that is reflected to the primary. When the converter is leaving a freewheeling mode of operation, the ZVS turn-on for switches S_1 and S_4 cannot occur for the converter proposed in [14]. The reason for this is there is no flying capacitor in the converter which provides a path for the current to flow through when the converter enters into a freewheeling mode of operation. If there is enough transformer leakage inductance energy to discharge the output capacitance of these devices when the converter is leaving a freewheeling mode of operation then only the switches can turn ON with ZVS. When considering the rare case for the converter is under the operation of light load condition then these switches will not turn ON with ZVS. Finally by comparing the proposed converter using flying capacitor with the converter proposed in [14] the proposed one has a better light-load efficiency because the two of its switches can always be turned ON with ZVS, irrespective of the load.

IX. RESULTS

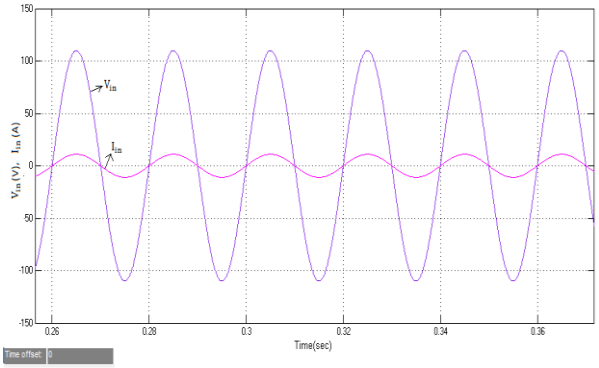


Fig.9. Input voltage and current

Fig.9. shows that the input current waveform is in phase with the input voltage waveform. The PFC function is achieved.

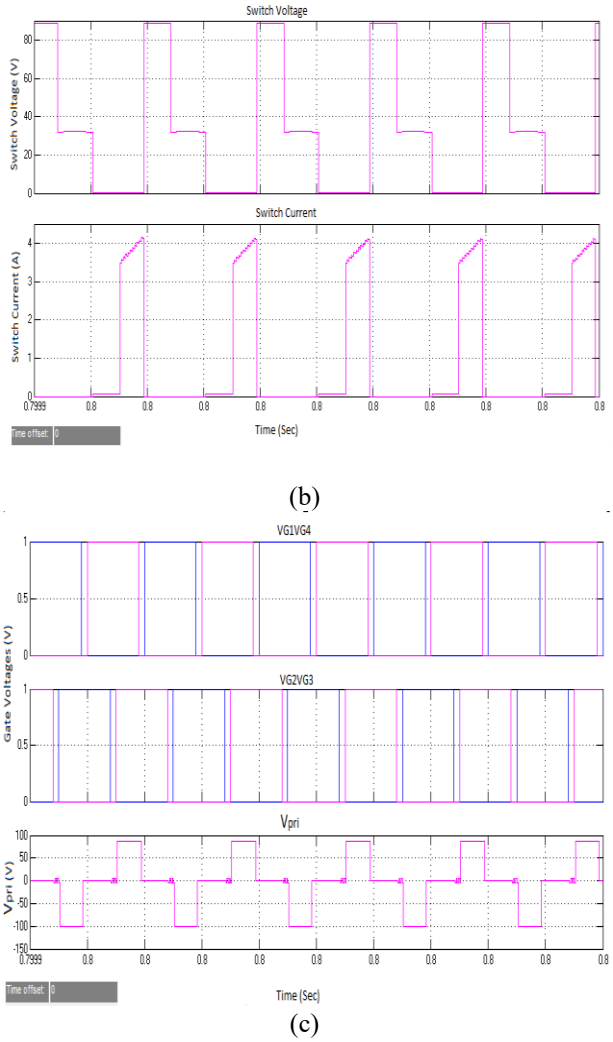


Fig.10. Typical converter waveforms.
(a) switch voltage and switch current
(b) pulses for the switches S1,S2,S3,S4 and the primary voltage of the main transformer.

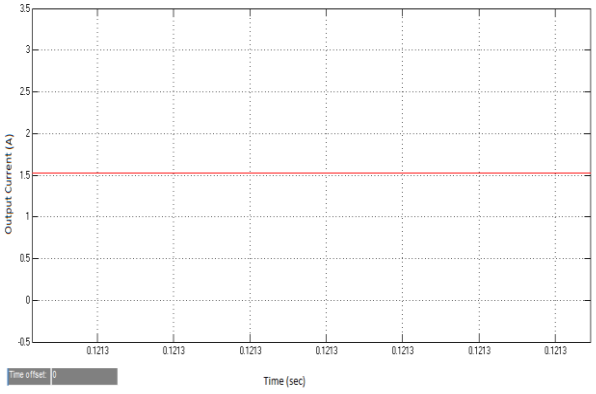


Fig.11. Simulation result of output current

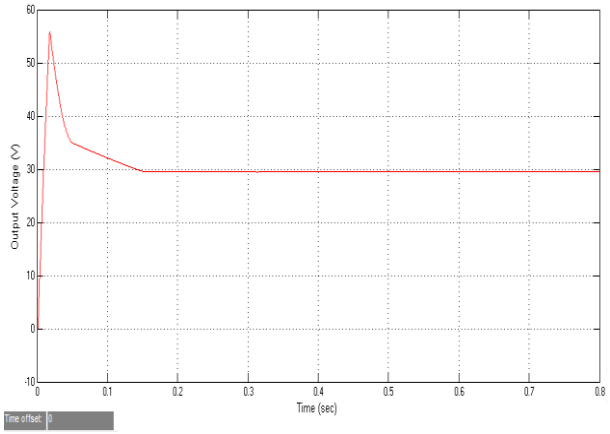


Fig.12. Simulation result of output voltage

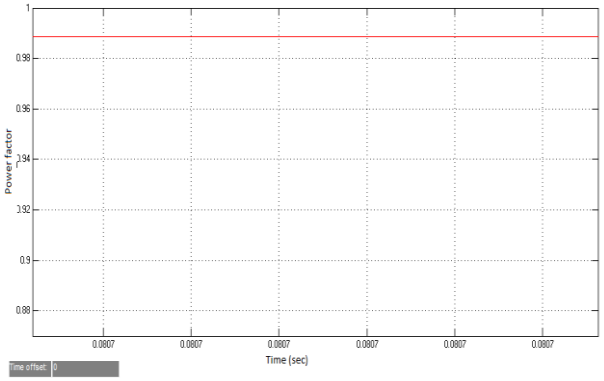


Fig.13. Simulation result of power factor

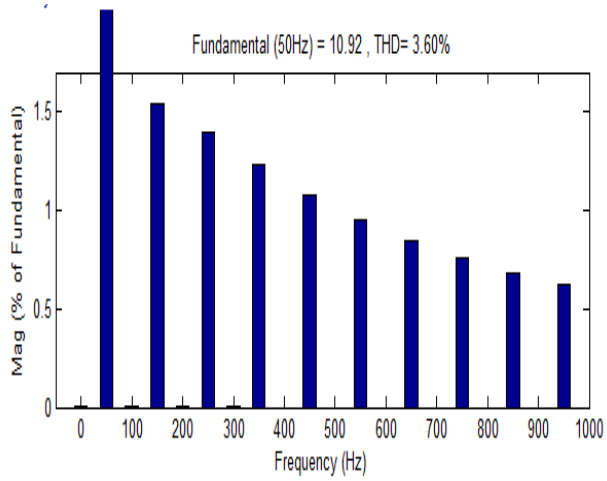


Fig.14. Simulation result of total harmonic distortion

X. CONCLUSION

A two phase interleaved single stage PFC using standard phase-shift PWM was presented in this paper. In this paper, the operation of the converter was explained and. It is seen that best power factor is obtained in case of interleaved boost converter. It is found that the proposed interleaved boost single stage PFC reduced the harmonicsin supply current thereby improved the power factor.

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